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ORBITAL INVESTIGATION OF PROPELLANT DYNAMICS IN A LARGE ROCKET BOOSTER

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

DEFINITION OF SYMBOLS

Symbol	Definition
h	liquid level, meters (inches) - measured from tank bottom
t'	second stage burn time, seconds
t	time after liftoff, seconds
a	longitudinal acceleration of vehicle, meters per square second (feet per square second)
g_o	9.8 m/sec^2 (32.17 ft/sec^2)
ω	frequency, hertz (cycles per second)
η	peak-to-peak amplitude, meters (inches)
ζ	damping ratio
τ	period, seconds
B_o	Bond number, $ar^2/(\sigma/\rho)$
r	tank radius, meters (inches)
σ	liquid surface tension, newtons per meter (pounds force per foot)
ρ	liquid density, kilograms per cubic meter (slugs per cubic feet)

ORBITAL INVESTIGATION OF PROPELLANT DYNAMICS IN A LARGE ROCKET BOOSTER

SUMMARY

Experimental data on the dynamics of liquid hydrogen in the 6.6 m (260 in.) diameter tank of an S-IVB stage during boost, at S-IVB stage cutoff, and in orbit are presented. For the boost phase of flight, the amplitude of the sloshing liquid decreased from approximately 0.25 m (10 in.) at the beginning of S-IVB stage boost to a minimum of about 0.038 m (1.5 in.) as the liquid level moved past the baffle. The frequency during the S-IVB stage engine burn increased from approximately 0.44 to 0.70 Hz (cps) and showed good agreement with predicted values.

During orbital coast, periods of the liquid hydrogen oscillation were measured through a range of accelerations from 2.0×10^{-5} g_0 to 4.4×10^{-4} g_0. Period data taken while the acceleration was varying with time did not agree with either the predicted natural or coupled periods. Nearly steady-state conditions existed for the 8.0×10^{-5} g_0 acceleration, and the 300 to 330 second slosh periods measured at this acceleration were close to the predicted value of 315 seconds. The good agreement between experiment and "high-g" theory (i.e., theory neglecting surface tension and contact angle effects) at this very low acceleration tends to verify the validity of Bond number as a criterion for defining high-g conditions with regard to liquid sloshing.

INTRODUCTION

Space flights to the moon or further space explorations will have as mission profiles waiting orbits or other engine-off low gravity coast periods after which the engine must be restarted. To accomplish such flights, the propellant dynamics in low gravity must be understood and controlled. Propellant dynamics problems occur in the following phases of flight:

(1) Boost

(2) Engine cutoff (transition from high to low acceleration environment)

(3) Orbit.

Several analytical investigations of low gravity fluid dynamics have been made by Satterlee, Reynolds, Saad, Benedikt and Fung [1-4]. Some experimental investigations have been made in which low gravity conditions were simulated in tests on the ground; the results of one of these are presented by Satterlee and Reynolds [1]. A Saturn IB liquid hydrogen orbital experiment has been performed to evaluate the hydrogen vent and engine restart systems of the S-IVB stage in an orbital environment. This experiment is discussed by Swalley, Platt and Hastings [5] and in MSFC documents [6,7]. As a part of the experiment, data were obtained on propellant (liquid hydrogen) dynamics in the S-IVB stage during boost, at S-IVB stage engine cutoff and in orbit. These data are unique with regard to the tank size, acceleration range and test duration for which they were obtained. This report presents these propellant dynamics data and compares them with the results of analytical investigations.

DISCUSSION

Apparatus

The experiment was conducted in an S-IVB stage which was launched July 5, 1966, by the uprated Saturn I flight designated AS-203. The S-IVB stage liquid hydrogen tank and the locations of the propellant utilization probe, thermocouples and liquid-vapor sensor are shown in Figure 1. The propellant utilization probe was a capacitance type of liquid level sensor designed to operate during the high acceleration of boost but not to operate at the low acceleration levels in orbit. The thermocouples and liquid vapor sensor shown were those which gave propellant dynamics data in orbit. The overall dimensions of the tank, deflector and baffle, and also the location of the television camera are shown in Figure 2. The photographs in Figure 7 show the portion of the tank viewed with the television and indicate that a large part of the tank wall was blocked from view by the deflector and baffle. The lines on the tank wall were 0.61 m (24 in.) apart.

Detailed descriptions of the instrumentation can be found in MSFC Memo R-AERO-F-135-66 [6]. All data were telemetered to the ground.

Results

The propellant dynamics data from the liquid hydrogen orbital experiment are presented for the boost, injection and orbit phases of the vehicle flight. In general, amplitudes and frequencies were measured for the sloshing liquid during boost and in orbit. The propellant reaction to the acceleration change at the second stage engine cutoff is presented based on visual data from video tape.

Boost. - Propellant sloshing during boost must be minimized to keep control disturbances small and to prevent severe unsettling of the propellant at engine cutoff (during transition from the high acceleration of boost to the low acceleration environment of orbit). The S-IVB stage has a baffle installed to minimize this sloshing at the end of S-IVB first burn and to eliminate or reduce the agitation of liquid caused by transition from high to low acceleration. The data from the propellant utilization probe were used to determine the slosh amplitude at the probe and the frequency. The location of the maximum slosh amplitude was estimated from the television record and used with the assumption that the slosh wave was first mode to determine the maximum amplitude at the wall. Since no attenuation factor was used and since the location of maximum amplitude was estimated, the amplitude data are approximate. However, the video tape of the propellant during second stage boost tends to confirm that the amplitudes presented are correct.

The slosh amplitude at the probe and the maximum amplitude at the wall are presented in Figure 3 with the damping predicted for the deflector and baffle. (The damping values are from Ryan and Buchanan [9].) Figure 3 shows a rapid decrease in slosh amplitude during the first 80 seconds of second stage boost, and minimum points in the amplitude curves at about 143 and 265 seconds. Figure 4 shows that the liquid surface was in contact with the curved portion of the tank wall for approximately the first 80 seconds of second stage boost, and the surface was near the deflector and baffle when the minimum amplitudes occurred. During the last few seconds of second stage burn, while the liquid surface was below the baffle, a sharp increase in sloshing amplitude occurred. To prevent this amplitude build-up, the baffle should be located so that the liquid surface at cutoff is above and very near the baffle.

The frequency during second stage boost increased from approximately 0.44 to 0.70 Hz (cps), as shown in Figure 5. The predicted frequencies were in good agreement with these experimental values. The second stage acceleration, shown in Figure 6, was used with high-g theory [8] to calculate the predicted natural and coupled slosh frequencies of Figure 5. These accelerations are the preflight predicted values and are nearly the same as the accelerations which existed in flight.

Engine Cutoff. - The kinetic energy in the sloshing propellant at the end of boosted flight is the main source of energy for the liquid dynamics at cutoff. As discussed by Ryan and Buchanan [9], this energy from boost slosh can result in large amplitude sloshing or spraying of the liquid when the acceleration is drastically reduced, as at engine cutoff.

In the AS-203 flight, second stage engine cutoff occurred at about 435.5 seconds after liftoff. Propulsive venting of the liquid oxygen tank, begun 0.2 second after cutoff, provided an acceleration of approximately 2.0×10^{-4} g_o which tended to keep the liquid hydrogen in the tank bottom. The sequence of photographs in Figure 7, taken from the video tape, shows part of the propellant dynamics at cutoff. At t = 422 seconds, the liquid surface appeared to be smooth and ripple-free so that the bottom of the liquid hydrogen tank was clearly visible. Shortly after cutoff (t = 442 seconds), the liquid surface was covered with small ripples. At t = 474 seconds, a geyser of liquid was in view moving from left to right. At t = 495 seconds, the liquid was returning to the tank bottom. The following observations were made from the video tape:

(1) The liquid wet the baffle two seconds after engine cutoff.

(2) The liquid surface moved first to the left of the television view, then the geyser (shown in Fig. 7 at t = 474 seconds) came into view moving up and to the right. The geyser appeared to be above the deflector at 23 seconds after cutoff.

(3) The upward movement of liquid stopped about 58 seconds after cutoff and the liquid from the geyser began to resettle.

(4) At 157 seconds after cutoff, the propellant was again below the baffle and apparently settled in the tank bottom. Magnification of the slosh amplitude occurred as expected and was successfully controlled by the use of baffle, deflector and oxygen vent thrust.

Orbit. - Knowledge of forces and moments exerted on an orbiting vehicle by the sloshing propellant is essential to the design of efficient attitude control systems. Propellant sloshing frequency and amplitude are important factors in determining these forces and moments. The acceleration, tank size and propellant properties are among the factors which define slosh frequency.

Longitudinal acceleration of the orbiting S-IVB stage was provided primarily by propulsive venting of the oxygen and hydrogen tanks. A record of the longitudinal acceleration for the orbiting S-IVB is shown in Figure 8. These accelerations [6] are computed values based on the vent nozzle characteristics and the properties of the vapor being vented. The acceleration spike near t = 6000 seconds in Figure 8 was produced by a fuel lead, and the near zero acceleration at 11,000 seconds was achieved by closing the vents.

At the end of each orbit, as the vehicle was passing over the United States, a relatively large acceleration was imposed on the vehicle for a short period of time. This resulted in the series of smaller spikes shown in Figure 8. Because of the shorter period associated with this higher acceleration, and the longer recording times afforded by the overlapping ground stations, most of the sloshing period measurements were taken during these spikes. Points at which the thermocouples and liquid-vapor sensors indicated slosh are indicated by the filled symbols.

The Bond number is a ratio of body forces to cohesive forces and is used in defining low gravity regimes. The Bond number variation with flight time is shown in Figure 9. The tank radius was selected for the characteristic dimension. For the liquid hydrogen, a kinematic surface tension (σ/ρ) of approximately 26.76 cm^3/sec^2 was assumed. The resulting figure is similar to Figure 8 from which the acceleration values were taken. In general, the Bond number was above 100 for most of the flight .

Figure 10 shows the output of a thermocouple and a liquid vapor sensor at a particular location. These curves are typical of those used to determine the sloshing periods.

The slosh periods measured during orbital coast are presented in Figure 11 as a function of longitudinal acceleration, a/g_o. For comparison, a theoretical natural period and a theoretical coupled period are shown. The natural period was calculated using the linear potential theory [8] for tanks of arbitrary shape and does not include the effects of surface tension, contact angle or viscosity. Since for the Bond numbers under consideration this theory gives essentially the same frequencies as the theory of Satterlee and Reynolds [2], which does include surface tension and contact angle, it was thought to be more accurate for this tank shape. The values for coupled period were obtained from a flight simulation which included the control system, the rigid body dynamics of the vehicle, and a spring-mass slosh model. This slosh model was also based on the linear potential theory [8]. A more detailed discussion of this analysis, including the equations used and some typical results, are presented by Ryan and Buchanan [9].

Together, Figures 8 and 11 seem to indicate that the slosh frequency is strongly influenced by the time rate of change of longitudinal acceleration. Data taken for $d(a/g_0)/dt \approx 0$ exhibit very little scatter and match very closely theoretical natural period. On the other hand, data for $d(a/g_0)/dt \neq 0$, showed much more scatter and indicated periods substantially shorter than either of the predictions. The usual procedure for slosh calculations has been to ignore the effect of $d(a/g_0)/dt$ and, as indicated in Figure 5, this has proved to be adequate for the high-g case. Since, under low-g conditions, the fluid reacts more slowly, the frequency cannot change quickly enough to compensate for a rapidly changing longitudinal acceleration. The data presented here seem to show that for low-g calculations, this effect should be included. The good agreement between experiment and theory at $a/g_0 = 8.0 \times 10^{-5}$ in Figure 11 tends to verify the importance of Bond number in defining high-g conditions with regard to liquid sloshing. The high-g theory (i.e., theory neglecting surface tension and contact angle effects) gave good predictions of sloshing period at these high Bond numbers even at this very low acceleration level.

The axial distances between thermocouple and mean liquid level (Fig. 12) for the thermocouples which gave period data varied from about 0.076 to 0.56 m (3 to 22 in.). There were not, however, sufficient data to determine either the amplitude or direction of the sloshing motion. From the television record of the orbital flight, some motions of the liquid were discernible but, because the liquid at the tank wall was not in view, it was impossible to determine amplitudes or verify the period data.

CONCLUSIONS

For the boost phase of flight, the amplitude of the sloshing liquid decreased from approximately 0.25 m (10 in.) at the beginning of S-IVB stage boost to a minimum of about 0.038 m (1.5 in.) as the liquid level moved past the anti-slosh baffle. The frequency during the S-IVB stage engine burn increased from approximately 0.44 to 0.70 Hz (cps) and showed good agreement with predicted values.

During orbital coast, periods of the liquid hydrogen oscillation were measured through a range of accelerations from 2.0×10^{-5} g_o to 4.4×10^{-4} g_o. Period data taken while the acceleration was varying with time did not agree with either the predicted natural or coupled periods. Nearly steady-state conditions existed for the 8.0×10^{-5} acceleration, and the 300 to 330 second slosh periods measured at this acceleration were close to the predicted value of 315 seconds. The good agreement between experiment and high-g theory (i.e., theory neglecting surface tension and contact angle effects) at this very low acceleration tends to verify the importance of Bond number in defining high-g conditions with regard to liquid sloshing.

For verification of theory including the effects of surface tension and contact angle, experiments in low gravity and at low Bond number ($0.1 < B_o < 100$) are required. Experience gained in the present investigation would make it possible to locate the instrumentation in such a way that accurate measurements of amplitude and interface shape could be obtained in addition to the frequency data. If experimental verification of the low gravity analytical tools could be achieved, accurate predictions of the interaction of the vehicle control system with propellant dynamics would be possible for all phases of future vehicle flights.

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama, February 10, 1967
932-40-03-00-62

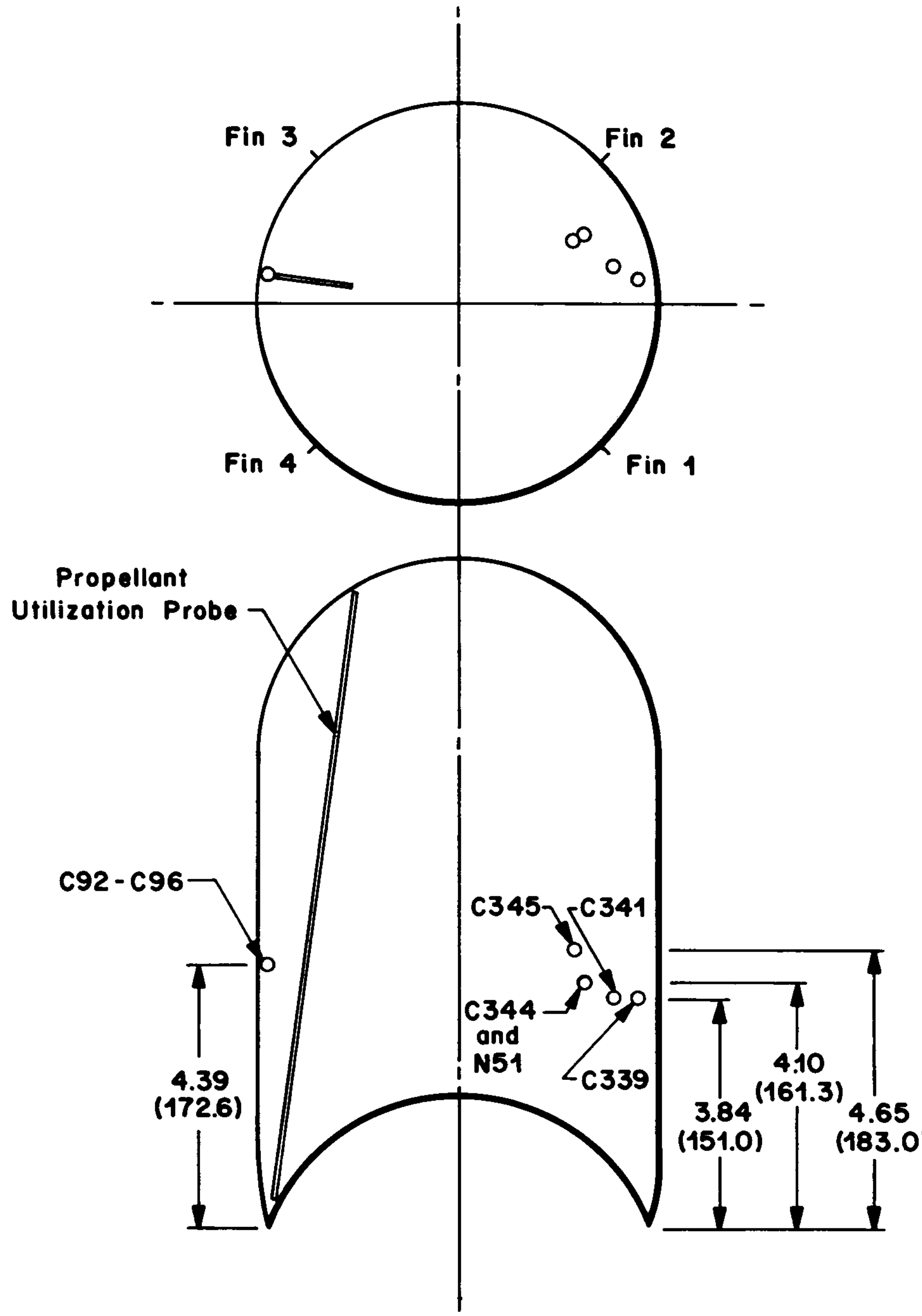

FIGURE 1. LOCATION OF THERMOCOUPLES, LIQUID-VAPOR SENSOR AND PROPELLANT UTILIZATION PROBE

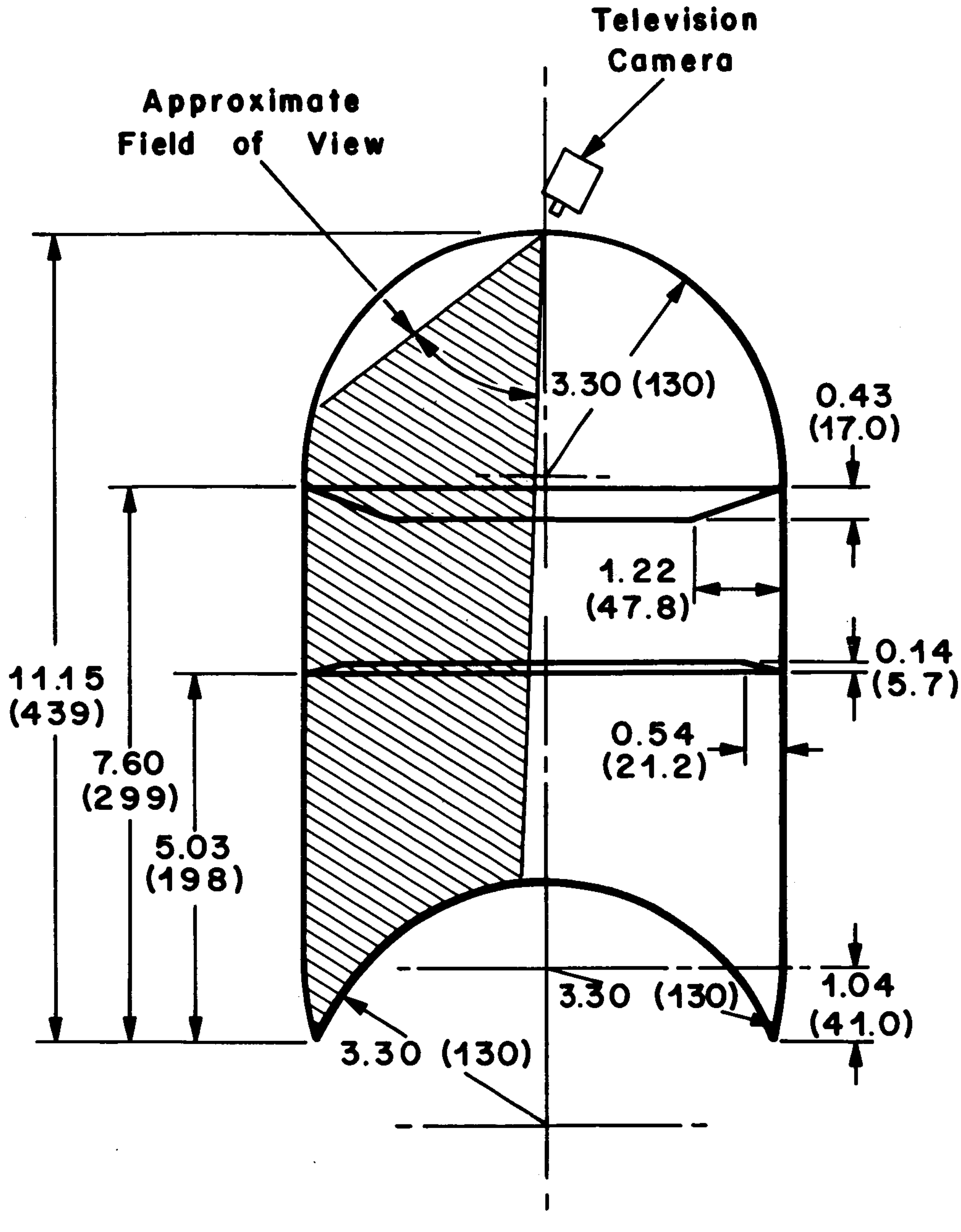

FIGURE 2. LIQUID HYDROGEN TANK DIMENSIONS

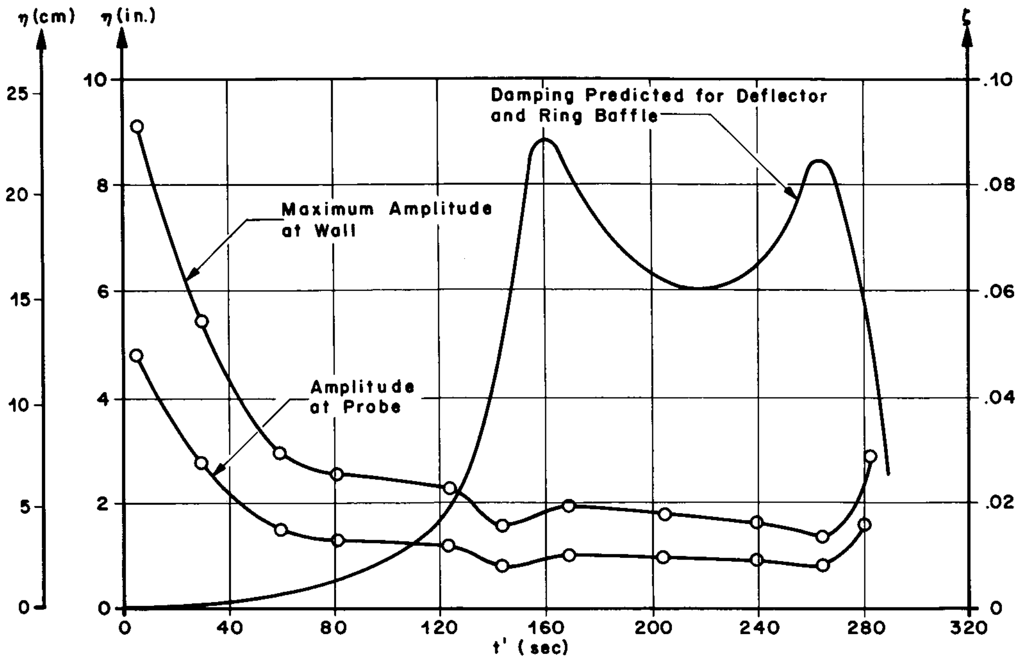

FIGURE 3. SLOSH AMPLITUDE AND PREDICTED DAMPING DURING SECOND STAGE BURN

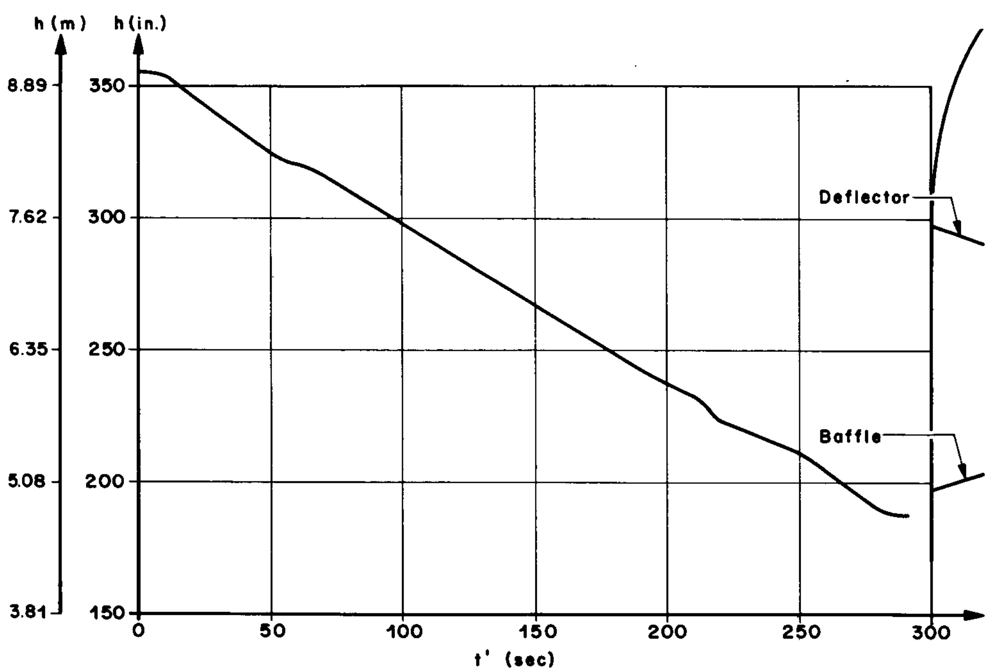

FIGURE 4. LIQUID HYDROGEN LEVEL DURING SECOND STAGE BURN

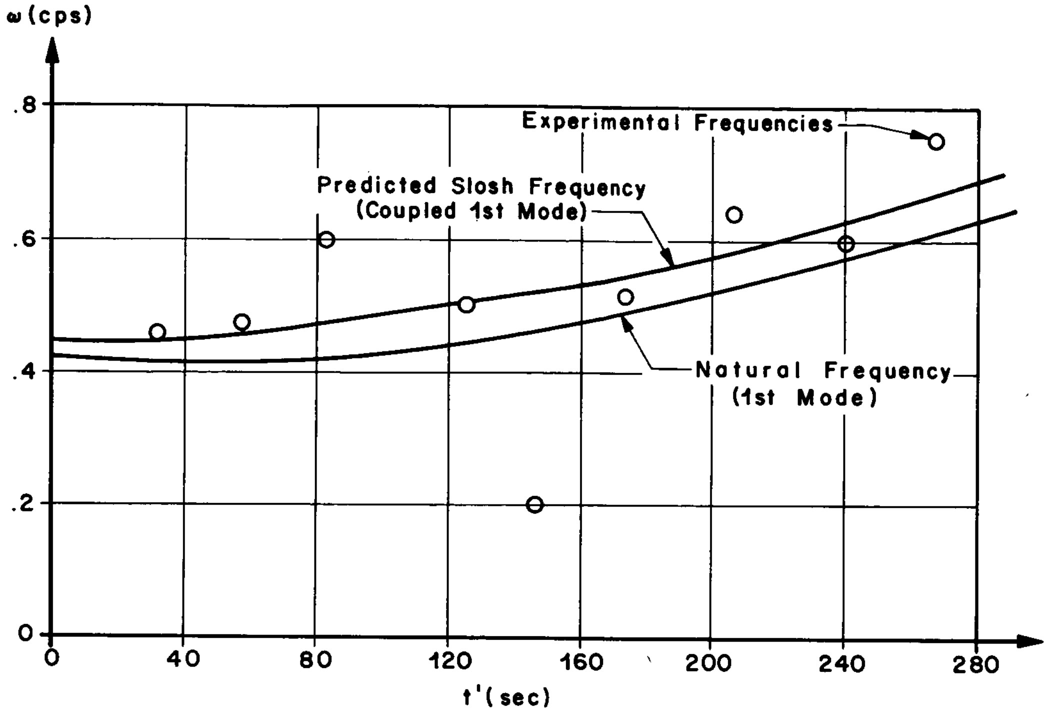

FIGURE 5. SLOSHING FREQUENCIES DURING SECOND STAGE BURN

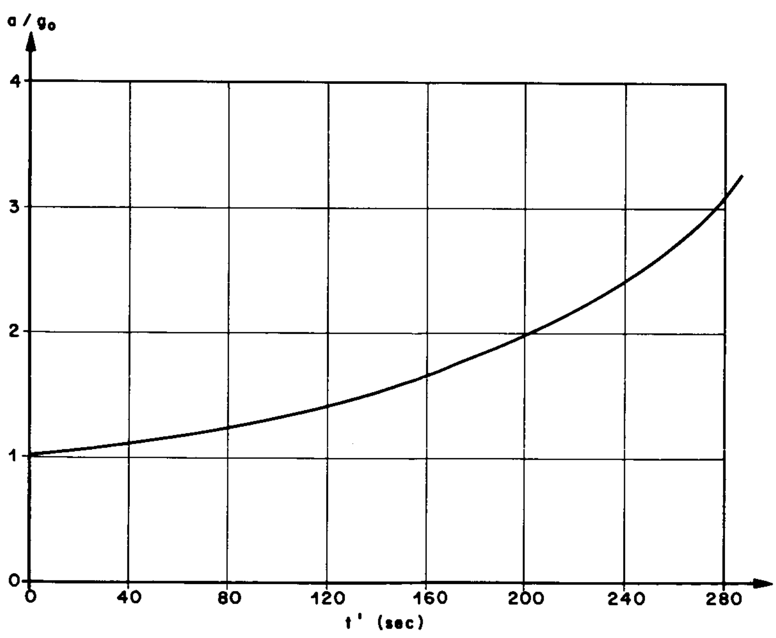

FIGURE 6. ACCELERATION DURING SECOND STAGE BURN

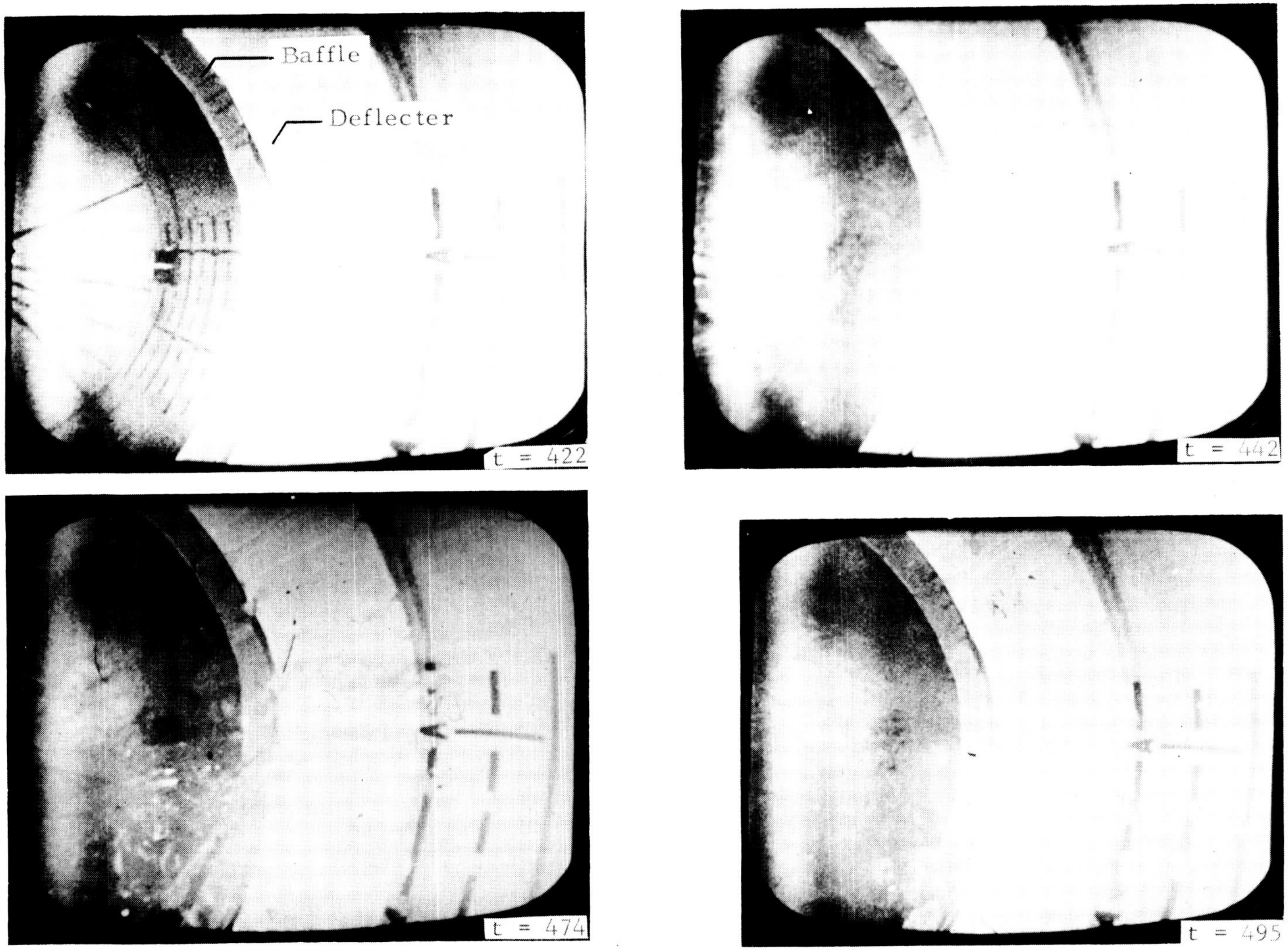

FIGURE 7. PROPELLANT DYNAMICS AT SECOND STAGE CUTOFF

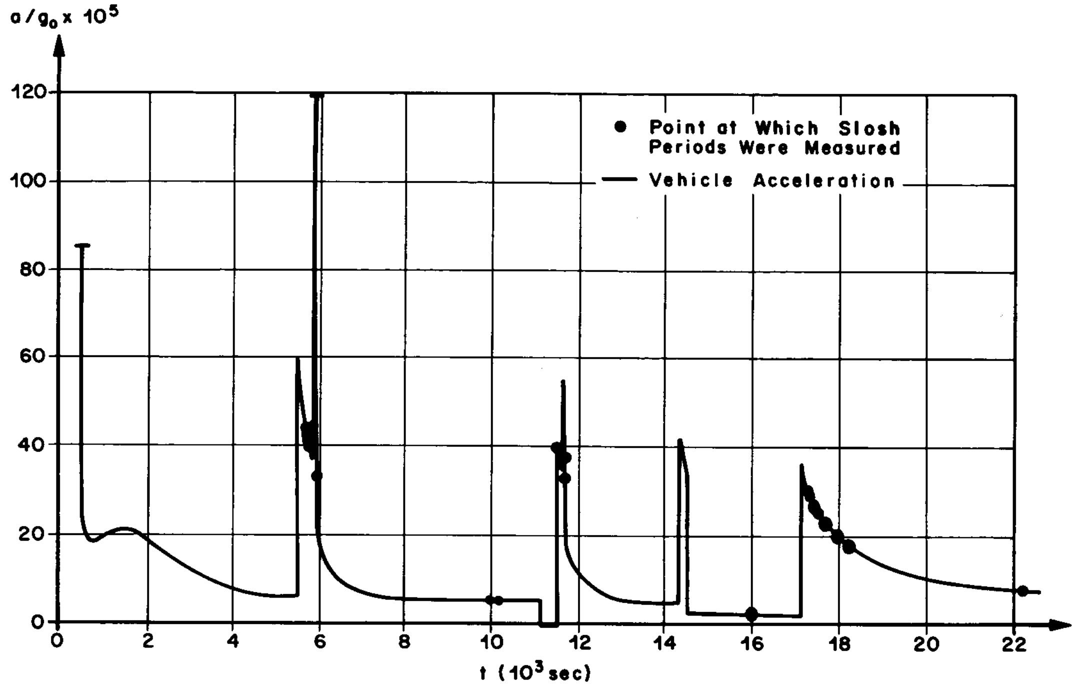

FIGURE 8. ACCELERATIONS DURING ORBIT

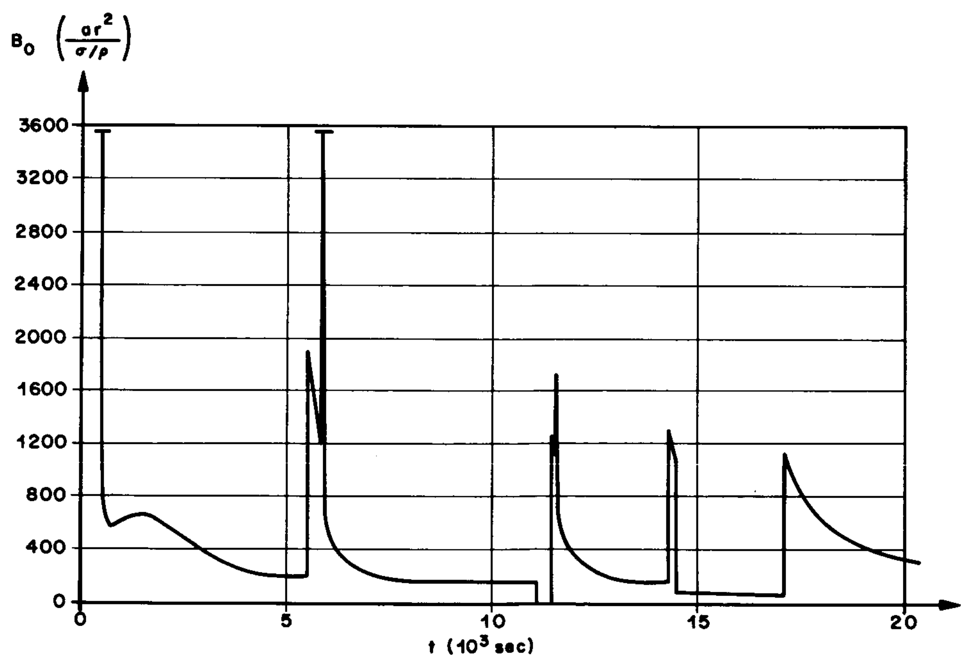

FIGURE 9. BOND NUMBERS DURING ORBIT

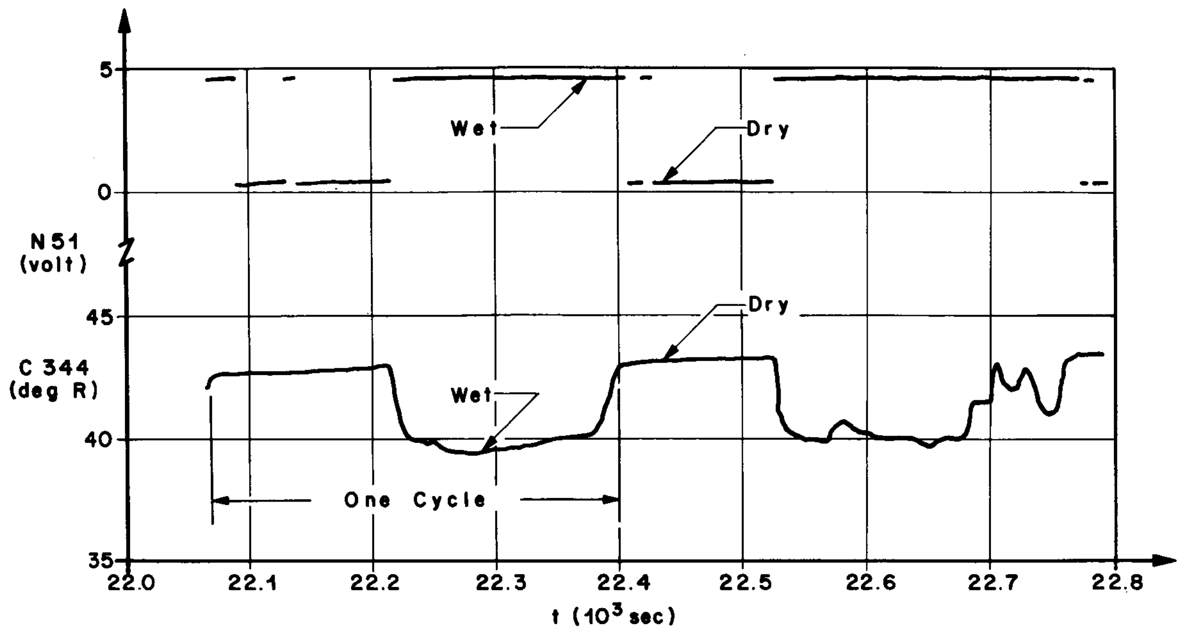

FIGURE 10. COMPARISON OF LIQUID-VAPOR SENSOR AND THERMOCOUPLE READINGS AT ONE LOCATION

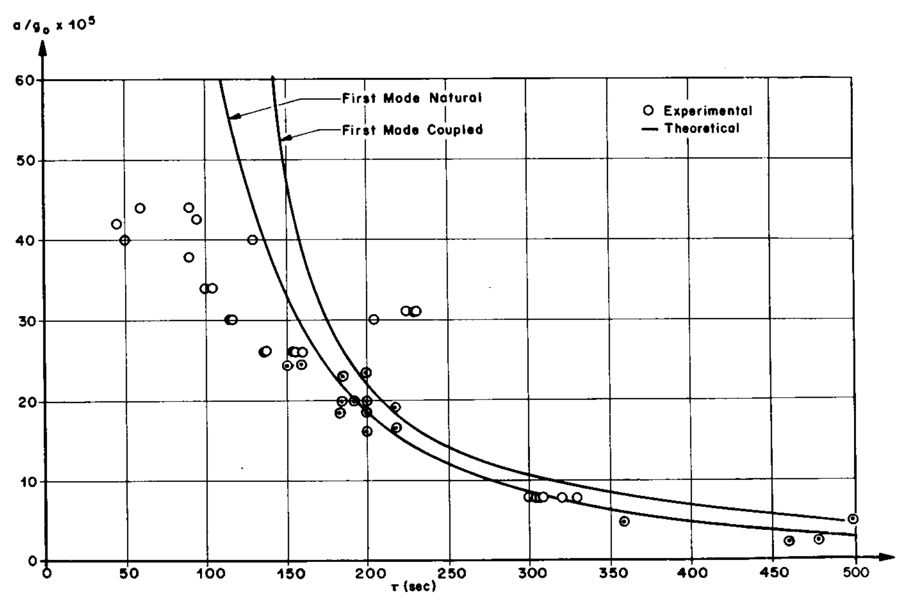

FIGURE 11. COMPARISON OF EXPERIMENTAL AND PREDICTED SLOSH PERIODS IN ORBIT

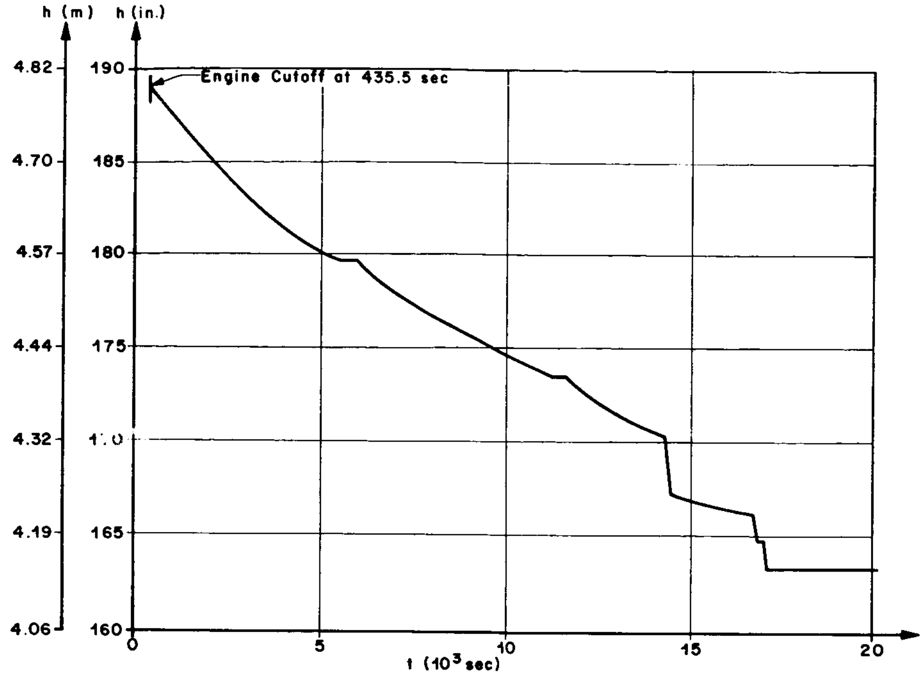

FIGURE 12. LIQUID HYDROGEN LEVEL DURING ORBIT

REFERENCES

1. Satterlee, H. M.; and Reynolds, W. C.: The Dynamics of the Free Liquid Surface in Cylindrical Containers Under Strong Capillary and Weak Gravity Conditions. Stanford University Technical Report LG-2, 1964.

2. Reynolds, W. C.; Saad, M. A.; and Satterlee, H. M.: Capillary Hydrostatics and Hydrodynamics at Low g. Stanford University Technical Report LG-3, 1964.

3. Benedikt, E. T.: A Study of Propellant Behavior at Zero Gravity. North American Aviation Report SID 66-286, 1966.

4. Fung, F. C. W.: Dynamic Response of Liquids in Partially Filled Containers Suddenly Experiencing Weightlessness. Cornell Aeronautical Laboratory Report No. AG-1995-S-1, 1965.

5. Swalley, F. E.; Platt, G. K.; and Hastings, L. J.: Saturn V Low-Gravity Fluid Mechanics Problems and Their Investigation by Full-Scale Orbital Experiment. Proceedings of Symposium on Fluid Mechanics and Heat Transfer under Low Gravity held Palo Alto, California, 1965.

6. Minutes of AS-203 First General Evaluation Meeting, Memo R-AERO-F-135-66, July 15, 1966, Marshall Space Flight Center, Confidential.

7. Minutes of AS-203 Summary Meeting No. 2, R-AERO-F-154-66, August 8, 1966, Marshall Space Flight Center, Confidential.

8. Lomen, D. O.: Digital Analysis of Liquid Propellant Sloshing in Mobile Tanks with Rotational Symmetry. General Dynamics Technical Report GD/A-DDE64-062, 1964.

9. Ryan, R. S.; and Buchannan, H.: An Evaluation of the Low-g Propellant Behavior of a Space Vehicle During Waiting Orbit. NASA TM X-53476, 1966.

NASA-Langley, 1967 —— 27